

## CHAPTER 2 - FLOOD PROOFING PERFORMANCE

This chapter presents in narrative form information on how flood proofing measures performed when tested by flooding. The information presented was gathered by an experienced engineer who viewed the structures and the flood proofing measures after they were subjected to floodwater. The structures are numbered in accordance with the numbering system used in Tables 1 and 2 of Chapter 3. A short discussion of the flood event precedes each respective group of structures. Photographs of individual structures or flood proofing measures are shown if they were available and if they were considered to be of value in understanding why the flood proofing measure either was successful or failed.

### CLIVE, IOWA

On the evening of May 9, 1986, an intense short-duration thunderstorm west of Clive, Iowa, resulted in flash flooding along Walnut Creek. There was little warning to residents of rising floodwaters. Velocities were only significant near the creek, and debris was not a problem. A prolonged wet period prior to the flood had saturated the soil. The typical soil profile of the area around the structure is a clay loam over a sand strata.

**STRUCTURE 1.** This house had a full basement. The walls were reinforced concrete with 2 feet exposed above the soil. The house was elevated some with fill placed around the house to promote runoff away from the home. This house was considered to be dry flood proofed. No structural or water damage occurred to the house; however, scour resulted in a soil loss of approximately 3 feet at an above-ground pool adjacent to the creek.

**Lesson.** The flood proofing system worked even though the area soils were saturated prior to the flood event. Damage from hydrostatic force did not occur to the basement walls because the walls were reinforced, the walls were not totally below “normal” grade (because fill had been placed around the house), and the flood event was very short.

### CENTRAL MICHIGAN

Beginning September 10, 1986, and lasting until September 12, 1986, 13 inches of rain fell over central Michigan. This rainfall resulted in flooding that lasted 48 hours and longer in some areas.

#### *ALMA, MICHIGAN*

**STRUCTURE 2.** A local convenience store with its back facing the Pine River was flood proofed with 2-foot-high steel floodshields in place at doorways to protect against the 100-

year flood. Flood proofing had been incorporated into the design of this building, which had a slab-on-grade foundation and masonry walls, in order to meet local building requirements. As part of the flood proofing system, the external utilities had been elevated on timber posts.

The flood of September 1986 overtopped the floodshields by 6 to 9 inches. This resulted in 3 feet of water entering the building and causing extensive damage to the contents of the store. No structural damage occurred. At the external utilities, scouring occurred at the base of the timber posts that supported the utilities because the end of the downspouts from the roof gutters were improperly located. Also, no splash aprons were provided at the outlet of the downspouts. Continued scour could have resulted in premature loss of the utilities, depending on the depth of post embedment.

**Lesson.** An apparent insignificant item such as downspout location threatened the utility supports and could have caused utility failure if the post embedment depth had been too shallow. The main flood proofing system failed because of inadequate design height, which allowed the measure to be overtopped. Higher floodshields may have provided protection; however, had they been higher, the hydrostatic force against the walls of the building may have exceeded the design and caused structural failure of the building walls.

#### ***MIDLAND, MICHIGAN***

**STRUCTURE 3.** This structure represents several buildings that had basements with no windows and were considered to be "dry flood proofed." These structures were flooded by backwater from the Tittabawase River. Flood marks matched, within a few inches, the 100-year flood from the published flood insurance study (FIS). Velocity was not a factor, as neither hydrodynamic loads nor impact loads caused any damage. Floodwater depths were less than 2 feet, and the structures were inundated for about 2 days. Floodwater was against each structure. The primary variable in whether or not structures were damaged was the basement wall material. Of the 10 buildings generally inspected, 6 had concrete block walls (5 of which were damaged) and 4 had poured concrete walls (2 of which were damaged).

**Lesson.** Because the buildings had no basement openings, floodwaters could not enter the buildings and equalize hydrostatic force. Much of the surrounding soil was clay, which expanded when it became saturated. The hydrostatic force caused the ultimate damage and failure of the measure. It should be noted that the poured concrete walls sustained less damage than the concrete block walls.

**STRUCTURES 4, 5, 6.** These structures had basements with concrete block walls. Two structures failed along the rear basement wall, where the longest unsupported horizontal spans occurred. The other structure failed along the front basement wall, where the wall was not connected to the sill plate. When this front wall failed, it allowed water to enter, resulting in unequal force on the interior partition walls and causing the partition walls to fail. Another

resident in the area with similar basement construction prevented damage to his structure by filling the basement with water to counteract the external hydrostatic force.

**Lesson.** It is very difficult to satisfactorily flood proof a basement if floodwater comes in contact with the foundation walls. Basements should not be considered to be dry flood proofed unless the foundation walls and basement floor have been designed and constructed to withstand hydrostatic force, the structure can withstand buoyancy force, a sump pump and drain system is in place, and sewer drain lines have backflow prevention valves installed.

**STRUCTURE 7.** This structure represents multifamily apartment units. Units with reinforced poured concrete walls fared much better than those with nonreinforced concrete block walls as the reinforced concrete walls had more strength to withstand the hydrostatic force. Also, in some units, the saturated soil conditions caused basement floor uplift due to hydrostatic force and cracked the basement slabs because there was no water in the basement to counteract the uplift force. This uplift was transported to the support beam through the column support, which caused the flange of the I-beam to buckle.

**Lesson.** Tests show that unreinforced poured concrete walls provide more capacity to resist hydrostatic force than do unreinforced concrete block walls of the same thickness. For buildings with block or concrete foundations that have long, unsupported wall spans, offset walls could have been used to support each other and add strength. Failure may still have occurred in such a large flood as the September 1986 storm, but the added strength could have prolonged the walls' ability to sustain themselves against lesser events.

For all units, the basement slab should have been thicker and reinforced. It would then have withstood the hydrostatic force that resulted in damage to the basement floor and to the main I-beam. Structural damage could have been prevented in all units by the use of blow-out plugs. An alternative to prevent building damage due to basement wall or floor failure would have been to fill the basement temporarily with clean water. Another alternative could have been to fill the basement permanently with gravel fill--but only after breaking up the concrete basement floor to prevent hydrostatic force buildup.

## **CRYSTAL CITY, MINNESOTA**

From July 20 to July 24, 1987, thunderstorms dropped 8 to 14 inches of rain, resulting in severe flooding. This flooding lasted 1 to 3 days, which played a role in damaging foundation walls because the surrounding soils became fully saturated. Debris and high-velocity flows were not a factor because much of the flooding was located in backwater areas.

**STRUCTURE 8.** This two-story, single-family house, which had a full basement foundation of 8-inch-thick non-reinforced concrete blocks, was located 80 feet from Bassett Creek. The house had a 21-foot-wide attached garage, and the entire house was flood proofed with a floodwall.

The flood proofing measure ensured a good foundation for the floodwall and positive cutoff of seepage below the wall. A subsurface drainage system was also constructed. A sump pit with a fully automatic sump pump that had manual override and a high-water alarm was installed. A clay soil mixture fill was placed against the outside of the floodwall to direct drainage away from the wall and reduce underground seepage. For windows outside the floodwall, galvanized window wells were installed.

In the July 1987 flood, the finished basement of the house was inundated by 2 feet of water. This was not caused by overtopping of the floodwall but rather was a result of the sump pump discharge pipe being placed too close to a window well around a window located outside the floodwall. The soil around this window well quickly became saturated and water seeped through the window well. After the owner became aware of the problem, the discharge line was rerouted and flooding subsided, but not before significant financial losses had occurred.

**Lesson.** An apparently insignificant item of sump pump discharge pipe placement resulted in failure of this system. This structure was also subject to failure due to collapse of the nonreinforced basement walls. Apparently, the sump pump and drain system were large enough in capacity to reduce hydrostatic force on the basement walls to the extent that the nonreinforced walls did not collapse even though saturated soil conditions existed. Flood proofing a structure with a basement is very difficult and is generally not recommended, especially in areas of longer duration flooding where the floodwater is in contact with the structure and no reinforcement exists in the conventional 8 inch-thick concrete block walls.

**STRUCTURE 9.** This two-story, single-family home was located 70 feet from Bassett Creek. The lower level of the house was a walkout basement. This house was flood proofed with a floodwall. The floodwall enclosed the entire rear of the house, protecting the walkout basement, and was tied to the house foundation using steel to provide added strength. The footings of the floodwall were reinforced poured concrete and were larger than normally required for a retaining wall of this size to prevent overturning from hydrostatic force. The wall was constructed with 12-inch concrete blocks reinforced both horizontally and vertically. A sump pump and a drain system were installed to drain the enclosed plaza area.

At this site, flooding lasted 36 hours. No major damage occurred. Only a small amount of water accumulated in the basement, entering through two unforeseen weak points in the flood proofing measure. First, an abandoned well pipe in the basement had been improperly sealed. Second, the present owner of the house did not know of the need to turn the sump pump on "automatic" mode.

**Lesson.** When designing an effective flood proofing system, the designer must always look at small details to anticipate any "weak points" in the system where water can enter. Any "weak point," no matter how small, can cause system failure.

**STRUCTURE 10.** This one-story, single-family house, located 470 feet from Bassett Creek, had a full basement with walls of 12-inch nonreinforced concrete blocks. The house was flood proofed with permanent window shields, and earthen fill was placed against the shields and the house foundation. However, no sump pump was installed, and backflow preventors were not included on sewer outlets. Consequently, 2½ feet of water collected in the basement and damaged contents and stored materials. Minor cracking was also evident along the front foundation wall.

**Lesson.** This system failed for two reasons: (1) no sump pump and drain system were installed to evacuate minor seepage and (2) water entered the house through the sewer system, which did not have a back-flow device installed. This resulted in 2½ feet of basement flooding. Major structural damage to this structure could have occurred from the hydrostatic force on the nonreinforced foundation walls, which are what caused the observed cracks in the front foundation wall. Obviously, saturation of the soil adjacent to the basement walls did not occur or the nonreinforced walls would have collapsed. The use of 12-inch concrete blocks versus the standard 8-inch concrete blocks aided in preventing major damage. Unless the walls are reinforced to resist the hydrostatic force, the soil is impermeable and floodwater does not come in contact with the foundation walls, or a drain system and a sump pump are installed around the perimeter of the basement with enough capacity to reduce the hydrostatic force, the structure should be wet flood proofed by evacuating all damageable items from the basement and purposely flooding the basement with clear water to prevent further foundation wall collapse due to hydrostatic force. If the walls were reinforced to withstand hydrostatic force due to saturated soil, buoyancy due to hydrostatic force would have to be accounted for.

**STRUCTURE 11.** This one-story, single-family house, located 160 feet from Bassett Creek had a full basement foundation of 12-inch-thick nonreinforced concrete blocks. The house was flood proofed with a partial 12-inch-thick block floodwall around the rear window and doorway entrance to the basement. The block in the floodwall was reinforced both horizontally and vertically. For windows outside the floodwall, window wells were installed. The plaza area outside of the rear door and behind the floodwall was small and roofed, so no sump pump was installed for internal drainage. Instead, a gravity area drain was used. During the flood of July 1987, the basement of the house was flooded with 2 feet of water because of seepage through the basement walls caused in part by semi-saturated soils. However, no structural damage occurred to the house.

**Lesson.** A sump pump drain system that can operate with a battery or with generator power should always be installed. As with Structure 10, a nonreinforced block foundation wall forming a basement should not be relied upon to prevent major wall failure in an area where soils can become saturated due to floodwater around or near the structure. Flood proofing basements is never recommended unless the full effects of hydrostatic force, including buoyancy, are designed for.

**STRUCTURE 12.** This two-story, single-family house, located 40 feet from Bassett Creek had a walkout basement with sliding glass doors. The house was retrofitted with the most expensive flood proofing project in the neighborhood. A floodwall enclosed the entire rear and left sides of the structure.

The floodwall was a T-shaped wall that stood 6.3 feet high. The initial 3-plus feet of the wall was reinforced poured concrete (to withstand hydrostatic force). It was topped by 12-inch-thick reinforced masonry blocks. The wide footings were tied to the wall with reinforcing steel. Extensive landscaping was also incorporated into the design of this flood proofing project to increase the aesthetic appeal of the home. A sump pump was located in the plaza area outside the house but was protected by the floodwall.

During the flood of July 1987, water entered the house; the apparent weak link in the flood proofing system was a window on the non-flood proofed side of the house. The window sill was below the level of the floodwall. Railroad ties were used as a barrier around the window; however, the ties had not been sealed to each other or the foundation wall. Seepage through the ties entered the house through the window sill, with 2 inches of water accumulating in the walkout basement. However, the rear doors were opened to allow floodwater to flow to the outside plaza area. This prevented further floodwater buildup and the sump pump drained the plaza. Other houses in the area had used galvanized window shields. The window well of railroad ties was inferior to the rest of the flood proofing system and was apparently constructed by the homeowner as an afterthought.

**Lesson.** A very good and probably expensive flood proofing system was not totally successful due to one “weak” spot that apparently seemed insignificant to the homeowner.

## **MONTGOMERY COUNTY, TEXAS**

In May and June of 1989, heavy rainfall resulted in significant flooding in low-lying areas of Montgomery County, Texas. In the Splendors Farms subdivision, several flood proofed structures experienced flooding.

**STRUCTURE 13.** This house was located less than one-half mile west of Peach Creek and approximately 1 mile north of Waterhole Branch. The wood-frame house had an extended masonry foundation, with the lower area used as a garage and storage area. The primary flood proofing measure used at this house was an earthen ring levee constructed around the structure. The levee was not overtopped; however, an inadequate internal drainage system, in combination with continuous rain for 1 month and seepage through the levee, resulted in high water within the levee and flooding in the garage and storage area.

**Lesson.** The internal drainage system (1) must be designed in accordance with the event frequency being mitigated by the primary flood proofing measure, which, in this case, was the

levee; (2) must account for the expected levee permeability; and (3) must account for the expected duration of riverine or coastal flooding. The secondary flood proofing measure, which was elevation on extended foundation walls, did not fail.

**STRUCTURE 14.** This one-story brick house, located approximately 1.3 miles east of Peach Creek and approximately 50 feet from Gully Branch, had a concrete slab-on-grade foundation. A vinyl-coated nylon fabric floodshield was installed as the primary flood proofing measure. During nonflooding conditions, the shield was stored in a metal gutter at grade. The gutter extended over a drain system around the perimeter of the house. The drain led to a sump pump, which was used to remove seepage from the drainage system. During anticipated flooding, the shield was raised and attached onto metal clips in the brick siding. The height of the floodshield in a raised position was 43 inches. Across openings such as doors and windows, the doors and windows provided support. Across the patio, decorative metal railing was used to provide structural support for the shield. However, at these railings, no lateral bracing for the shield was incorporated into the design. To provide lateral support, the owner used a board propped between the rail and wall to transfer some of the hydrostatic load. During the May and June 1989 storms, flood depths rose to 15 inches above grade at the house. Subsequent tests indicated that the railing would have failed at a depth of 43 inches. During these flood events, water did not enter the house. The external air conditioning unit was properly elevated and was not damaged, but an external propane tank was not properly anchored and floated off its base.

**Lesson.** This flood proofing system worked this time. If the flooding had been higher, the system would have failed due to the lack of adequate support of the floodshield across windows, and at the patio. The openings at windows should have been closed with proper metal or wood closures to provide strength to the fabric floodshield. Across the patio, the railing providing support must be properly supported to the floor by diagonal braces. Some type of solid backing to the floodshield, such as plywood, should have been placed between the railing and the floodshield.

**STRUCTURE 15.** This one-story brick house, which had a slab-on-grade foundation, was located approximately 80 feet from Gully Branch. The house had a permanently installed system of brick "steps" in front of openings to prevent the flow of water through doorways. During the May flood, the flood level reached 15 inches above grade and overtopped the "steps."

**Lesson.** Flood proofing measures that can be eventually overtopped can result in damages as if the measure were not in place. Damages could be worse than without the measure if the flood event is of short duration and the flood proofing measure (such as a floodwall or levee that is overtopped) holds the floodwater in the protected area longer. Freeboard, as a "factor of safety" above the level of flood protection desired, should always be considered. The level of flood protection should always be as high as possible for measures that, if overtopped, result in flooding equal to or worse than without protection.

**STRUCTURE 16.** This one-story, brick house, which had a slab-on-grade foundation, was located one-quarter mile east of Peach Creek. The home was flood proofed with a floodshield (full shield height of 47 inches) similar to the measure installed at Structure 14. However, this measure incorporated two unique design features. First, the floodshield enclosed a large patio area. This added to material and installation costs, increased interior drainage area, and required a larger portion of the shield to be supported by metal railing rather than the building wall. The railing supporting the shield around the patio area included diagonal bracing to the patio floor to support lateral loads. Flood depths reached the top of the shield, but the railing showed no signs of being overstressed. Second, at the front entrance of the house, a free-standing, nonreinforced brick pillar, rather than the more conventional metal railing, was used to support the shield. This pillar, which was 4 feet high and 16 inches wide, had no overlapping joints at successive layers or any ties into the adjacent building walls or porch slab. During the May flood, this pillar failed due to the hydrostatic force, allowing the shield to slump, which created a low point. Floodwaters entered the house and reached depths up to a few inches due to the short duration of the flood crest.

**Lesson.** This flood proofing measure was very successful except for the one weak point--the nonreinforced pillar. If the duration of the flood crest had been long, total measure failure would have occurred because the "protected" area would have filled with floodwater to the level of the flood crest.

**STRUCTURE 17.** This one-story, split-level house was elevated on 8-inch-square timber piles spaced 9 feet apart on width and 7 feet apart on length. The front half of the house was elevated 5 feet above grade, and the rear half was elevated 8 feet above grade. During the floods of May and June 1989, flood depths of 27 inches resulted in high-velocity flows that caused localized scour 3 to 6 inches deep around the piles. However, the house suffered no structural or interior damage because the piles were driven to a depth greater than the scour depth.

**Lesson.** It is important to always keep in mind the potential for erosion and scour when determining the depth of piles, posts, columns, piers, and supporting foundations.

## **CENTRAL COAST, SOUTH CAROLINA**

On September 21 and 22, 1989, Hurricane Hugo, a Category 4 hurricane, battered the coast of South Carolina. The hurricane was followed by rainfall from early morning to early evening on September 25, 1989. During the hurricane, storm surges reached 13 to 20 feet above the mean sea level and winds ranged from 60 to 120 miles per hour. Damage from this hurricane was caused by storm surge flooding, surge-related erosion, wave action, high winds, and rainfall. Warnings had been issued days before the storm hit.

## ***SURFSIDE BEACH, SOUTH CAROLINA***

**STRUCTURE 18.** This one-story, single-family manufactured home, which was located approximately 150 feet from the ocean, was elevated on thirteen 4½-inch-diameter steel columns. The lower area was enclosed and used as a living space. The house measured 56 feet by 24 feet, with the longest dimension perpendicular to the ocean. Beneath the house was a concrete slab at grade (pre-storm). This slab was cracked and undermined, but it held in place and acted as a diaphragm and provided rigidity. Approximately 2 to 3 feet of sand, measured horizontally, scoured from under the edge of the slab. Foundation anchorage beneath the slab was provided by steel columns embedded in 28-inch-diameter concrete collars. The embedded depth of the steel columns was unknown. The wall studs were connected to the substructure using hurricane fasteners.

**Lesson.** This home sustained little structural damage. Even though scour undermined the concrete slab, the columns were embedded deep enough in the ground to prevent damage due to column collapse. A perimeter footing around the concrete slab--constructed to a depth below anticipated scour would have added more safety factor to this structure. The lower living area should not have been enclosed, as enclosures at that elevation allow hydrodynamic force to impinge against the structure. The structure should also have been oriented such that the longest dimension was parallel, not perpendicular, to the ocean. It is surprising that this structure did not fail because the incorrect structure orientation and the enclosed lower area subjected the structure to severe hydrodynamic force and increased localized velocities.

**STRUCTURE 19.** This one-story, single-family, wood-frame home was elevated on 18 brick columns. There were two rows of seven columns on the south side and two columns at both ends on the north side. The center portion of the lower area was supported on extended foundation walls, which formed a lower area enclosure used as a living space. The brick columns were 16 inches by 16 inches and were connected into a spread footing by two rebars, thus making piers. The spread footing was 36 inches in diameter and 12 inches deep. The brick columns were connected to floor beams with rebar, which was bent at the top and placed through a hole in the beam.

During Hurricane Hugo, the base slab of the lower area enclosure and the oceanside columns were undermined. As a result, the lower area enclosure cracked and part of the foundation collapsed. The primary cause of damage was the lack of proper embedment of the foundation. Wind damage was minimal, as the roof, siding, and windows remained undamaged.

**Lesson.** Piers should not have been used in an area that can expect high-velocity floodwater and scour. Only piles embedded to depths greater than expected scour should be used. The concrete slab should have been protected from scour by the placement of perimeter footings to depths greater than expected scour. The lower area should not have been used as a living space. It should also not have been enclosed, as this creates higher localized velocities capable of increased scour as water flows around the obstruction.

**STRUCTURE 20.** This one-story house measured 43 feet by 50 feet, with the broadest dimension perpendicular to the ocean. The house was elevated on thirty 16-inch by 16-inch masonry chimney block columns. Each column was supported on a shallow footing embedded approximately 2 feet, thus forming piers. The columns were connected to the footings by one No. 6 rebar and to the floor beam by bent-over rebar. As a result of the hurricane, seven columns were undermined, pulled from the beam-to-column connection, and collapsed. Other columns were undermined, settled, and separated slightly from the floor beam.

**Lesson.** The weak points in this flood proofing system were threefold: (1) in a high-velocity area, such as along the ocean where oceanfront property is subject to erosion, only piles made of wood or steel should be used; (2) the piles should be embedded below the ground surface a distance greater than the maximum expected scour; and (3) the narrowest dimension of the structure, not the broadest, should face the ocean.

#### ***GARDEN CITY, SOUTH CAROLINA***

**STRUCTURE 21.** This multistory structure faced the ocean and was elevated approximately 7 feet on deeply embedded wood piles. The lower area was enclosed with siding of limited strength. During the hurricane, the piles endured significant debris impact, with no indication of structural distress. None of the pile-to-beam connections failed, but they were not constructed as designed. The piles were notched on top to provide a "seat" for the floor beams. However, the notches were not used. Rather, the beams spanned the top of the piles and were bolted to the beam with galvanized plates. This reduced the overall rigidity of the structure and led to more independent movement of the piles. Thus, the piles were less able to act as a unit and resist lateral wave impact forces.

Damage at this house was limited to the pool and patio and to the siding used to enclose the lower area. The siding had limited strength and, as such, it performed as a breakaway wall, shearing off at the main support beam. It is interesting to note that this house suffered no structural damage while the neighboring structure, which had a slab-on-grade foundation, was subject to similar forces and was destroyed.

**Lesson.** In this case, the piles were made of wood (which is acceptable) and were embedded below the ground surface far enough so scour was not a problem and the piles could resist the bending moment created by the hurricane force wind against the multistory building. Another key to the success of this flood proofing system was the breakaway siding enclosing the lower area of the building. The breakaway siding allowed water to flow relatively unimpeded (except for accumulated debris) under the structure. This reduced or eliminated a major problem--scour due to water having increased localized velocity as it passed around a larger obstruction created by nonbreakable siding.

The neighboring house with slab-on-grade construction was probably destroyed for two reasons: (1) the slab-on-grade house had to endure the hydrodynamic force of water directly impinging against the structure and (2) localized floodwater velocities were increased due to the obstruction to floodflows of the structure at grade. These increased velocities would have produced more localized scour, undermining the slab-on-grade foundation.

**STRUCTURE 22.** This two-story, single-family house was elevated on eighteen 10-inch-diameter wood piles embedded approximately 10 feet. Cross bracing and knee bracing were parallel to flow, with no bracing perpendicular to flow. This provided less area for hydrodynamic and debris impact loads. The main floor support beams were also parallel to flow to minimize the effects of wave impact. The beams rested in notches at the tops of the piles and were connected with 2<sup>3</sup>/<sub>4</sub>-inch bolts. The uplift connections between the floor joists and the support beams were galvanized metal hurricane fasteners. There was a 4-inch-thick concrete parking slab at grade beneath the piles. During the storm, this slab was undermined on the ocean side and partially collapsed. However, the collapse did not cause any structural problems. Water damage from storm surge and wave forces was limited primarily to an oceanside deck, the front entrance stairway, and the concrete parking slab. There was minimal wind damage because the owner boarded up the oceanside windows, roof eaves were kept to a minimum, and hurricane fasteners were used throughout the structure to form a continuous connection from roof rafter to foundation.

**Lesson.** This structure's flood proofing system proved to be very sound. Damage to the concrete parking slab could have been eliminated with perimeter footings embedded below the expected scour depth.

#### ***PAWLEY'S ISLAND, SOUTH CAROLINA***

**STRUCTURE 23.** This one-story, single-family home located several hundred feet from the ocean was elevated on square timber columns. The columns were connected to 4-foot by 4-foot by 3-foot concrete footings that were embedded just below the pre-storm beach level, thus forming piers. The massive size of the footings kept the structure upright, but the shallow embedment depth caused the columns to lean landward due to hydrodynamic force against the structure and loss of supporting soil around the footings due to scour.

**Lesson.** This flood proofing system would have been successful if not for the inadequate embedment depth of the pier footings. The cost to embed these footings deeper to be below scour depth and to enable the structure to better resist the hydrodynamic force would have been relatively insignificant at the time of initial construction. The best alternative, however, would have been piles driven deep enough to be below scour depth and to be able to resist the bending moment due to the hurricane force wind impinging upon the elevated structure.

**STRUCTURE 24.** This two-story, single-family structure was elevated on square timber posts connected to concrete footings. The footings were connected by a poured concrete grade beam. Steel plates in the footings were bolted to the posts. Several bolts and fasteners showed signs of significant corrosion and would not be easy to replace. The structure weathered the storm in spite of poor design of the shallow foundation.

**Lesson.** This flood proofing system was apparently adequate this time. However, the severely corroded metal fasteners may not provide the needed strength the next time this structure is tested. This shows that these types of fasteners should not be used where corrosion can occur. Proper maintenance may have prevented the corrosion. The problem here is that many homeowners will not provide the maintenance. A solution to the corrosion problem may be to replace the existing connectors with stainless steel or galvanized connectors and to use caulk to seal out salt water. The shallow foundation system should not be used in hurricane areas. See the “Lesson” for Structure 23.

**STRUCTURE 25.** This three-story condominium complex was elevated on concrete piles. All but one pile withstood the storm. The one pile that was destroyed was attached to a wooden bulkhead that acted as the "ultimate" nonbreakaway wall. This bulkhead was constructed directly in the front of the structure, facing the ocean, and did not fail, thus transferring the full wave force directly to the pile and causing it to fail. The base slab was undermined and collapsed.

**Lesson.** This flood proofing system sustained damage because of one basic mistake--constructing a nonbreakaway wall that (1) transferred hydrodynamic force to the supporting pile and (2) created higher localized velocities that scoured the soil beneath the base slab. The base slab could have been protected with perimeter footings embedded to below scour depth.

#### ***DEBIDUE BEACH, SOUTH CAROLINA***

**STRUCTURE 26.** This two-story, single-family oceanfront home was constructed partially on piles and partially slab-on-grade. The center portion of the lower area was wood-frame construction built up from the base slab, and the left and right sides were elevated above the inhabited lower area enclosure. The slab and piles were undermined, causing the center portion to list toward the ocean and the north side to completely collapse. The north side disconnected at the adjoining roof lines without structurally damaging the center portion of the roof.

**Lesson.** Three basic mistakes occurred with this system: (1) the slab-on-grade construction allowed hydrodynamic force to directly impinge on the structure and localized floodwater velocities to increase, creating increased scour potential; (2) the piles were not

embedded deep enough below grade; and (3) the concrete slab-on-grade did not have perimeter footings to prevent scour from occurring beneath the slab.

**STRUCTURE 27.** This one-story, single-family home was moderately elevated by concrete columns embedded only a couple of feet into the sand. The columns rested on shallow footings, thus forming piers. They were connected to the superstructure with bolts and fasteners attached to a wood post extending from the main support beam.

The storm's waves eroded the supporting sand, causing the oceanside portion of the house to lean. The differential settlement caused the house to crack from the floor beam to the roof line. The storm eroded sand from beneath the shallow footings, causing them to lose bearing capacity and leaving some of the piers in mid-air. The dead weight of the concrete piers caused the bolt connection at the wood post to fail. Also, the concrete pad under part of the building was undermined and broke off in sections.

**Lesson.** Two critical mistakes were made in the system design: (1) piers should not have been used where high velocities occur and (2) the embedment of the footings below grade was not below the scour depth. Piles embedded below the scour depth would have made this flood proofing effort successful.

#### ***CHARLESTON COUNTY, SOUTH CAROLINA***

**STRUCTURE 28.** This two-story, wood-frame house in Romain Retreat was elevated on eighteen 9-foot-high masonry columns with six additional columns at grade supporting the rear porch. The masonry columns were constructed of 8-inch by 12-inch by 12-inch masonry chimney units filled with grout and reinforced with four No. 4 rebars, with the overlap of spliced bars being only 6 inches. The columns were constructed over a concrete base slab, with rebars tying the columns to the slab, thus forming piers. The lower area was enclosed by brick walls that were not tied to the slab or elevated floor.

Most of the 24 piers collapsed from the storm. The connective fasteners, which were 2 $\frac{1}{4}$ -inch-wide by  $\frac{1}{8}$ -inch thick galvanized steel, failed under surge and wind forces. Each pier contained two fasteners, which were embedded in 12 inches of grout fill and connected to each side of the timber floor beams by two  $\frac{1}{2}$ -inch diameter bolts. The exposed portion of the fasteners were severely corroded. The failure occurred at the exposed (corroded) portion of the fasteners rather than at the bolts due to the loss of cross sectional area.

**Lesson.** The failure of the fasteners due to corrosion contributed to the overall system failure. Proper maintenance and the use of stainless steel or galvanized connectors protected from salt water could have prevented this. Thicker connectors would also have been helpful. The major system failure, however, was pier failure. This occurred because of four reasons: (1) inadequate embedment

depth below grade of the pier footings, allowing scour to occur below the footings; (2) inadequate reinforcing steel overlap length at splices that did not give the column the strength to resist wind forces against the two-story house; (3) perhaps inadequate column size; and (4) the lower area enclosure made of brick that did not break away and caused larger hydrodynamic force on the adjacent columns and increased localized velocities, causing increased scour. Piles should always be used in coastal areas that are subject to erosion. Piers should never be used unless the footings are protected from scour.

**STRUCTURE 29.** This house was similar in design to its neighboring house in Romain Retreat (Structure 28) in that a pier design was used, but this structure did not fail.

**Lesson.** There were several differences between this structure and Structure 28, which failed. First, larger concrete masonry units (measuring 8 inches by 16 inches by 16 inches) were used in constructing the columns. Second, heavier galvanized metal fasteners (measuring 2<sup>1</sup>/<sub>4</sub> inches by 1<sup>1</sup>/<sub>4</sub> inch) were used. These larger fasteners lessened the effects of corrosion. Third, breakaway wood lattice walls rather than brick walls were used to enclose the lower area, decreasing the effect of hydrodynamic force with no increase in local velocities and hence higher scour levels. Fourth, the pier embedment depth may have been greater. This pier-supported structure survived this test. However, piers are never recommended in a coastal area subject to scour potential.

**STRUCTURE 30.** This one-story, single-family home located in Isle of Palms was located behind a well-vegetated substantial dune system. The house was elevated on 7-foot-high masonry piers constructed from 12-inch mortared blocks. The storm surged 5 feet below the structure. The well-established lawn and dune helped prevent the scour of the piers.

**Lesson.** This structure probably would have failed due to scour beneath the piers if it had not been for the dune system.

**STRUCTURE 31.** This single-family house in Isle of Palms was located approximately 150 feet from the ocean. The house, which measures 40 feet by 50 feet, with the broadest dimension parallel to flood and wind forces, was elevated on 10-inch-diameter wood piles 9 feet above grade. The piles were cross braced with 2-inch by 12-inch wood both parallel and perpendicular to flow. Approximately 25 percent of the cross bracing in the outer bays perpendicular to flow was damaged due to surge forces and debris impact.

The house also had an at-grade deck of wood planks beneath the structure. Uplift from waves caused some of the deck planks to be removed from the deck framing. However, the wood deck was better than a concrete slab because erosion did not cause as much damage and repair costs were less. In addition, the access staircase to the house was enclosed from the handrail to the stair, adding surface area for wave and impact force which led to the failure of the stairs.

**Lesson.** Minimizing the amount of obstruction beneath the house to hydrodynamic force results in less structure damage.

**STRUCTURE 32.** This two-story, single-family home located approximately 150 feet from the ocean in Isle of Palms, was elevated on forty-eight 10-inch-diameter wood piles. The house was 48 feet by 42 feet, with the broadest dimension perpendicular to flow. Tensile bracing of the piles (consisting of ½-inch braided steel cable) was placed both parallel and perpendicular to flow. The house support beam sat in a notch on the pile and was bolted with ¾-inch-diameter bolts. Although a section of roof was damaged, the house was not significantly damaged.

**Lesson.** This flood proofing system worked because of two basic reasons. One, piles, rather than piers, were used in an area subject to coastal-related erosion. Two, the lower area was not obstructed by enclosed areas. It should be noted that this structure was cross braced with steel cable (minimal obstructive effect) and was not damaged like Structure 31, which used wood bracing (larger obstructive effect).

**STRUCTURE 33.** This two-story, single-family house in Isle of Palms was an example of extraordinary effort in coastal construction. The house was elevated by wooden posts above the flood event that occurred, and the lower area was enclosed with breakaway walls that were partially cut 3 feet below the house to create a weak point for clean shear off. Most of the breakaway wall did fail at the cut.

For this event, the utilities and duct work under the structure were not damaged by turbulence from water passing beneath the structure because they were sufficiently elevated. All duct work was encapsulated with plywood to prevent its being pulled off by water. When compared to the damage that occurred to utilities at nearby homes, this extra effort proved to be cost effective.

A concrete slab used for parking and storage beneath the structure was damaged due to erosion beneath the slab. The main house structure was strengthened by wooden posts from below grade to the roof. There was one joint, at the first floor, where adjoining posts were bolted together. Railing was placed between posts at each floor to further strengthen the structure. Each railing was screwed to the post with stainless steel screws, and each joint was caulked to seal out salt water mist and to prevent corrosion. Roof construction consisted of ¾-inch tongue-and-groove plywood instead of the normal ½-inch thick plywood. Thus, the roof was able to act as structural support for the framing. Before installing wood plank siding on the house, the builder predrilled each hole to avoid splitting the woodframe boards which could provide a weak point for wind damage.

The roof covering also survived well, as additional precautionary techniques were implemented during construction. Metal flashing was placed under the shingles at cap lines, the roof overhang was almost flush to the walls, and the ends of the shingles were sealed to the roof.

**Lesson.** Extra care and expense taken when designing and constructing a flood proofing system pay dividends when the system is tested. One item that was overlooked in the system was perimeter footings around the concrete slab to prevent scour under the slab. Another item was piles, which should have been used in lieu of posts in a coastal area subject to erosion.

**STRUCTURE 34.** This two-story, single-family, wood-frame house in Isle of Palms was located approximately 75 feet from the ocean. The house was elevated on piles at a level to accommodate the storm event without storm surge. Therefore, the floor system was inundated approximately 1 to 2 feet by the storm surge. Incoming waves caught the bottom of the floor joist and impacted the underside of the structure.

The house suffered severe damage. The entire oceanside wall and approximately 30 percent of the street wall were removed. The walls were ½-inch plywood sheathing coated with a stucco face. The sheathing and stucco cracked and broke at the damaged areas.

The floor joists on the street-side perimeter of the building failed. They were nailed at one end and bolted at the other. As the nails were pulled out, the beam acted as a lever to pry the bolted connection. The oceanside joists were also ripped out, but it could not be determined how they were connected to the supports. The floor joists were perpendicular to flow. Thus, they were ripped out by the flood force, although the floor itself remained in place by resting on the piles.

**Lesson.** The flood proofing system simply did not elevate the structure high enough to be above the storm surge. Less damage would have occurred to the house even at its existing elevation if the floor joists would have been oriented parallel to the storm surge.

**STRUCTURE 35.** This two-story, single-family home (also in Isle of Palms) was located approximately 30 feet from the ocean behind a riprapped embankment and was elevated 7 feet above grade on 36 piles that were 10 inches in diameter. The lower area was enclosed. The storm surge was higher than the lowest elevated floor. The ocean side wall and a section of floor were removed by the storm surge, and the main support beam failed. There was a masonry cinder wall extending from the slab to the elevated floor at the ocean side of the lower area enclosure. The connection between this wall beam may have been the cause of failure of the main support beam. In addition, much of the riprap became water-borne projectiles, which tore through the lower area. Also, the piles were cross braced perpendicular to flow, and the first row was destroyed.

**Lesson.** This flood proofing system had three basic problems. First, the riprap placement was a mistake since the riprap was forced into the structure by the storm surge. Second, the structure was not elevated high enough for this particular event. Third, the masonry wall enclosing the lower area transferred hydrodynamic force to the piles, adding to failure. The cross bracing between the piles perpendicular to floodflows probably accumulated debris, which, when combined with the impact of the storm surge driven riprap, caused pile failure.

**STRUCTURE 36.** This one-story, single-family home was elevated on wood piles. The wave crest just reached the underside of the structure, ripping away plywood sheathing on the frame and causing severe damage. The house shifted 2 to 4 inches landward. Several piles became misaligned. In the north wing, the entire wall and floor systems were destroyed because the principal support beam for the north wing was located perpendicular to flow.

**Lesson.** This structure may have not been damaged if the flood proofing system had elevated it above the storm surge. Also, alignment of the floor support beams parallel to the storm surge would have helped to reduce damage.

**STRUCTURE 37.** This two-story, single-family home in Isle of Palms was elevated 7.5 feet above grade on thirty 13-inch by 13-inch masonry block columns filled with reinforced concrete. The columns were supported by wooden piles embedded 12 to 18 feet below grade. The pile-to-column connection was provided by a concrete slab poured as a pile cap. The lower area was enclosed. Both the street and ocean sides of the lower area were enclosed with a breakaway lattice, which had 50 percent open area. During the storm, the lattice did break away as intended. The side walls of the lower area enclosure consisted of concrete blocks and windows. The column-to-beam connections were not properly galvanized. Overall, this house suffered very little damage, and the flood proofing system performed well.

**Lesson.** This flood proofing system elevated the structure sufficiently. The column support piles were embedded well below scour depth. The depth of the embedded piles provided strength from wind loading. Three additional measures that could have been included in the flood proofing system are (1) placing perimeter footings around the slab to prevent any scour under the slab, (2) building all walls of the lower area enclosure with breakaway materials, and (3) using connectors that are either stainless steel or galvanized metal and inspecting and maintaining them annually.

**STRUCTURE 38.** This one-story, single-family home in Isle of Palms was both elevated on concrete block columns and protected by a fairly large dune. The lower area was fully enclosed and used as a two-bedroom apartment. The lower area was destroyed, but no structural problems occurred to the elevated structure.

**Lesson.** The large dune probably saved this structure from complete damage due to storm surge and hydrodynamic force. The obvious major mistake with this structure was completely enclosing the lower area and using it as developed living space. This major obstruction, if not for the large dune, would have created such localized high velocities that scour plus the large hydrodynamic force transferred to the columns by the enclosure of the lower area may have destroyed the entire structure.

**STRUCTURE 39.** This one-story, wood-frame house in Isle of Palms was elevated on forty-two 8-inch by 8-inch wood posts. The posts were strapped and bolted to a concrete grade beam that

was embedded more than 12 feet deep. The central portion of the house was a 60-foot by 24-foot rectangle. Wings were attached to both ends, extending the width of the central portion of the house.

The elevating posts had bracing both parallel and perpendicular to flow. The floor beams were perpendicular to flow and were bolted and fastened to the posts. The construction of this house included extensive use of hurricane fasteners.

Wind forces dislocated and destroyed the southern wing, which had a relatively large surface area for the wind to act on due to the height of the inner wall and the distance the wall extended from the center of the house. The posts supporting the southern wing were pulled from their connections, but the fasteners did not fail. Rather, the posts cracked and pulled away from the connections. There was no apparent damage to the northern wing or to the center portion of the house.

**Lesson.** The flood proofing system for the structure was successful, but the wind proofing system was not. Larger connector attachment brackets would have prevented the detachment of the connectors from the wood posts.

**STRUCTURE 40.** This one-story, single-family home in the Isle of Palms was constructed of reinforced concrete and was elevated on 18-inch-square reinforced concrete columns which extended to the roof line. The columns were embedded deep enough to stabilize the structure, but the embedment depth was unknown. The floor system was not the typical wood frame but rather was 24-inch precast, prestressed double concrete tees locked together parallel to the shoreline. The beam-to-foundation connection utilized a bearing pad. A 9-foot by 16-foot portion of the lower area was enclosed with masonry block walls. These walls were not instrumental in providing structural support to the building and suffered no damage. This house withstood tremendous forces as evidenced by the neighboring restaurant that was completely destroyed.

**Lesson.** In "normal" flood proofing system construction, the nonbreakaway walls around the lower enclosed area would have created problems due to scour and increased hydrodynamic loading on the columns. However, in this case, the structure and the flood proofing system were integral to one another to such an "overdesigned" extent by "normal standards" that the presence of the nonbreakaway walls had no effect on this structure.

**STRUCTURE 41.** This one-story, single-family home in Isle of Palms was located only 20 feet from the ocean. The house was elevated on twenty 8-inch-square wood piles. The embedment depth was unknown but seemed to be adequate since the piles remained embedded even after 2 feet of sand was eroded by the storm. The piles had wood cross bracing perpendicular and parallel to flow. The lower area was enclosed with lattice breakaway walls that had 80 percent open area. A concrete slab at grade under the left side of the house was used for parking. This slab was undermined on the ocean side and collapsed after approximately 2 feet of sand was removed by the storm.

Hurricane fasteners were used extensively throughout the structure. The street and ocean side staircases also had hurricane fasteners and did not experience damage.

**Lesson.** The only apparent problem with this system was the lack of perimeter footings around the concrete slab to prevent scour. The wood cross bracing perpendicular to the storm surge should have been avoided by using cables if bracing was necessary in that direction.

**STRUCTURE 42.** This two-story, single-family home in the Isle of Palms, which was located approximately 50 feet from the ocean, was subject to severe on- and off-shore winds. The house was elevated on twenty 12-inch-diameter wood piles. Floor beams ran parallel to the flow and connected to the foundation with  $\frac{3}{4}$ -inch-diameter bolts with a single notch in each pile. The floor joists were toe-nailed to the floor beams. Hurricane fasteners were used on the other connections.

Surge forces removed approximately 65 percent of the horizontal wood plank wall on the ocean side. However, the most intense damage was the loss of the roof. The low-pitched gable with gable ends faced the direction of wind. The roof overhang was less than 1 foot. A window in the hip of the roof may have let wind in, which then caused the loss of the entire roof. Without the roof to act as a support for the walls, the walls fell outward. Hurricane fasteners had been used, but most of the house was infested with wood worms. The resulting poor wood quality resulted in the failure of the wall-to-roof connections.

**Lesson.** From a flood proofing system viewpoint, this system was not elevated high enough to be above the storm surge.

## **ST. LOUIS, MISSOURI, AND VICINITY**

During the spring and summer of 1993, extremely heavy rainfall over a prolonged time period occurred throughout the Upper Mississippi River basin. This rainfall on top of the wet soil conditions from the previous year created record flooding at many locations on the Upper Mississippi River, the Missouri River, and their tributaries.

### ***CRYSTAL CITY, MISSOURI***

**STRUCTURE 43.** This site consisted of three industrial/commercial buildings that were flood proofed by a partial ring levee tied into high ground at each end. The three buildings were slab-on-grade construction with exterior walls of concrete block. They were located 500 feet from the Mississippi River but were not in direct line of floodflows. Floodwater was against the levee for several days. The area soil was a silty clay. Flood warning time was several days. Flood debris at the site was average. The levee was a maximum of about 8 feet in height with a 6-foot top width. A majority of the levee was constructed with sideslopes at least as flat as 1 vertical to 2 horizontal. However, a portion was constructed with sideslopes of 1 vertical to 1 horizontal due to area constraints. The levee

was vegetated with grass. The levee interior was drained by gravity. The buildings each contained a sump pump. A flood fight was waged by placing sandbags on top of the levee. Since this was a partial ring levee, an escape route to high ground was available for those placing sandbags. The flood proofing system failed because of weakened levee conditions due to the narrow levee with sideslopes of 1 vertical to 1 horizontal, the prolonged flood duration, and overtopping at this location, which resulted in levee breaching.

**Lesson.** In this case, all parts of the flood proofing system functioned as intended except that the levee was overtopped, leading to levee breaching. Obviously, the levee should have been higher for this event. The levee failed where the sideslopes were 1 vertical to 1 horizontal. Levee breaching may not have occurred if flatter sideslopes (1 vertical to 3 horizontal or flatter) had been used. Sideslopes of 1 vertical to 1 horizontal are without question too steep for reliable levee stability. Without levee breaching, a successful flood fight may have been possible. This flood proofing system had a definite weak point -- that portion of the levee with the 1 vertical to 1 horizontal sideslopes. If not enough area was present for a levee with flatter sideslopes, a floodwall should have been built in that location.



Looking at the portion of the partial ring levee with flatter sideslopes. Note the opening that was closed with a closure structure that was successful. Note the sandbag flood fight on top of the levee.



Looking at the portion of the partial ring levee with steep sideslopes that resulted in complete failure due to breaching.

### ***HERCULANEUM, MISSOURI***

**STRUCTURE 44.** This site was about 300 feet from a backwater area connected to the Mississippi River. Flood duration and warning time were several days. The flood proofing system at this location consisted of a floodwall tied to high ground at each end. The system protected several mobile homes, a laundromat, and a store. At the highest point, the floodwall was 6 feet high. It was supported at intervals by means of concrete braces located on the “wet” side of the floodwall. The floodwall was overtopped by 3 feet, the mobile homes were destroyed, and the two permanent buildings were severely damaged.

**Lesson.** This system apparently worked well until it was overtopped. Floodwall bracing, if placed on the “dry” side of the wall, would provide more reliable support in a compression rather than tension mode. In regard to the wall being overtopped, a 9-foot-high wall (to eliminate overtopping in this event) probably would have been more expensive than relocating the mobile homes and two permanent buildings. Relocation out of flood-prone areas is the ultimate in flood proofing. Conducting a flood fight by raising the wall with temporary “flashboards” made of supported plywood may have been possible, although a 3-foot extension on a 6-foot wall would probably have reached the upper limits of reliability.



Looking at the floodwall and also the building on the “protected” side. Note the bracing on the “wet” side of the floodwall.

#### ***BARNHART, MISSOURI***

**STRUCTURES 45, 46.** These structures are both one-story, single-family houses. Structure 45 was protected by a floodwall with closures. Structure 46 was protected by elevation on extended foundation walls. Both were located in low-velocity flood areas away from the Mississippi River. Both flood proofing systems were overtopped by several feet. They are presented here as typical examples of flood proofing measures that work well when designed to protect against a particular flood. The flooding in 1993 was so record breaking that little can be learned from the failures of these systems other than the structures should have been protected to a higher level or relocated.

**Lesson.** Flood proofing systems that rely on elevation will probably have the protection level exceeded at some time in the future.

***ST. LOUIS, MISSOURI***

**STRUCTURE 47.** This was a commercial/government building measuring 75 feet by 1,000 feet. It was a slab-on-grade structure with the 1,000-foot side parallel to the floodflow. The building was about 50 feet from the River Des Peres. The structure was protected by a floodwall built in the late 1970's. The wall was generally 5 to 6 feet in height, with a maximum of 10 feet. The floodwall was between high ground and a railroad embankment serving as a levee. It protected against floods prior to 1993. During the 1993 flood, the floodwall was raised 4 feet with plywood extensions diagonally braced to the ground or laterally braced to the building with 2-inch boards. The system still overtopped, causing catastrophic flooding to the building and its contents. Floodwater velocity was not a problem.

**Lesson.** All flood proofing systems relying on barriers of some type to hold back floodwater at an elevation higher than the structures' first floors are subject to massive damage from overtopping. In this case, ultimate flood protection was not achieved, even with barrier construction and a valiant flood fight. In addition, a basic problem with wall flood proofing systems is the potential physical limit of raising the protection level during a flood fight. In this case, further reliable extension above the 4-foot level would have been increasingly difficult in contrast to a levee flood proofing system that, because of its wider base, would make a flood fight to greater heights much more feasible. A flood proofing measure to consider in commercial/industrial buildings is wet flood proofing if the damageable property can be permanently elevated or if a system of quick disconnects and evacuation can be employed.

***ST. GENEVIEVE, MISSOURI***

**STRUCTURE 48.** This was a commercial structure having 92,000 square feet of first floor area. It was a slab-on-grade structure with block/brick walls located about 1.5 miles from the Mississippi River. The flood proofing measure consisted of a levee about 6 feet high with 1 vertical to 3 horizontal sideslopes. The levee was located from zero to 6 feet from the structure. The levee tied to high ground at each end. Interior drainage was provided by two 10-inch pumps and gravity drains. Two additional pumps were installed during the 1993 flood. This flood proofing system was successful but only after a serious flood fight. The original levee, which was built with little engineering analysis, was composed of "lime screenings" (2-inch or less rock) with a plastic cover held in place with sandbags on the river side of the levee. During the flood fight, the levee was raised 6.5 feet with more "lime screenings" covered with plastic. An additional 3-foot raise was achieved with sandbags. This barrier, plus the interior drainage pumps, kept the structure flood free.

**Lesson.** This flood proofing system was successful because it could be raised to accommodate the 1993 flood levels. The raise was possible (9.5 feet on top of an original 6-foot-high levee) because the original flood proofing system base (the levee) was broad enough to satisfactorily accommodate a reliable raise to such an extent. In addition, the structure owners added more pumps

and provided the flood monitoring to give more reliance to their system. If this had been a "ring" levee, onsite flood monitoring would not have been advisable due to the inability to escape if the flood proofing system failed.

**STRUCTURE 49.** This structure was a commercial building measuring 60 feet by 100 feet with a slab-on-grade foundation. The exterior walls were concrete blocks. The flood source was about 1.5 miles away. The building was wet flood proofed to a depth of 10 feet. The 1993 flood was 12 feet in depth at this location--flooding utilities, equipment, and supplies that had been permanently elevated or stored on raised platforms. Damage to equipment, inventory, utilities, and the finished building interior was sustained.

**Lesson.** This building and its contents sustained damage due to 2 feet of flooding with failure of this system versus 12 feet of flooding if a system of barriers had been used and failed. Because of this, a wet flood proofing system shows system benefits even with failure due to inadequate elevation.

**STRUCTURE 50.** This one-story commercial building measured 60 feet by 60 feet with a slab-on-grade foundation and brick exterior walls. It was about 1.5 miles from the flood source. The flood proofing measure used was elevation on fill that extended up above grade about 12 feet. The 1993 flood was 10 feet above grade at the site.

**Lesson.** This system was successful because the building owner at the time of construction went to the extra expense of flood proofing to a higher level than most people do. It paid off in 1993. From strictly a flood damage viewpoint, this system was surpassed in effectiveness by only one other type of flood proofing--relocation out of the flood plain.

#### ***ST. LOUIS, MISSOURI, VICINITY***

**STRUCTURE 51.** This structure represented the numerous single-family homes and small commercial buildings that employed the flood proofing measures of elevation on piles, posts (columns), piers, and extended foundations walls. These homes were not in high-velocity areas.

**Lesson.** The only factor that separated a successful system from a failed system was whether or not the home was elevated so the first floor elevation was higher than the flood elevation. The type of support (posts (columns), piles, piers, or extended foundation walls) and the number, size, and composition of the supports (steel, wood, or concrete block) did not matter relative to the success of the flood proofing system. Bracing the supports also was not a factor relative to low-velocity floodwater. Bracing would be a factor, as would support size, type, and number and also the elevation measure used, for those elevated structures that could be affected by wind and hydrodynamic force. The real lesson is to always elevate as high as possible without becoming so high that mitigating wind and/or seismic forces becomes so costly compared to mitigating flood forces only that relocation becomes most feasible.



Looking at a typical structure elevated on extended foundation walls. Flood depth was about one foot above the main (elevated) floor. Note the elevated utilities on the outside wall.



Looking at a typical structure elevated on masonry columns with bracing. The structure is nontypical because it was the only elevated structure viewed that was above the flood.



Looking at a typical structure elevated on masonry columns that had water above the main (elevated) floor.

#### ***NUTWOOD, ILLINOIS***

**STRUCTURES 52, 53, 54, 55.** These structures were located in a row parallel to and about 200 feet from a levee that provided protection from the Illinois River. The levee was several feet high and was not considered a flood proofing system because it protected a very large area, not a single structure or single group of structures. The structures were single-family homes, with the first floors flood proofed by elevation on extended foundation walls. Floodwater velocity through the area was very high as a result of the adjacent levee overtopping. A levee breach in the area did not occur. The floodwater elevation was lower than the first floor elevations of the four structures. Scour was not apparent to any great degree in the area.

**Lesson.** In each of the four cases, the flood proofing system provided sufficient elevation for the first floor. The problem was the extended foundation walls that were constructed of concrete block completely enclosing the lower area with the exception of doors and windows. This enclosure created an obstruction to the high-velocity floodwater, thereby subjecting the walls to large hydrodynamic force. Two of the structures totally collapsed due to complete failure of the extended wall support system. No steel reinforcement or grouting in the walls was apparent. The other two structures were standing, but one side of the extended concrete block wall supporting the first floor collapsed on each structure. Examination of the collapsed walls on these two structures showed some vertical reinforcement of the wall with rebar and grout. No lateral reinforcement was observed. In all

four structures, the extended concrete block wall to support the structure should not have been used in an area close to a major river where high velocity during floodflows could occur. Supports such as columns, posts, or piles embedded sufficiently below grade should have been used, with piles being the preferred choice. Any enclosure of the lower area should have been of minimal strength to easily break under hydodynamic force.



Looking at Structures 52 and 53.



Looking at Structures 54 and 55.

### ***HERMAN, MISSOURI***

**STRUCTURE 56.** This was a large industrial building protected from backwater from the Missouri River by a floodwall. The floodwall was tied to high ground on each end, although it almost surrounded the building. Both the building and the original floodwall were old. The footings of the original wall were unknown. A portion of the original wall was still in place. The minimum distance from the wall to the building was 4 feet. The floodwall was raised on a permanent basis two times. The original wall height varied from zero to 4 feet. Each upward extension was 2 feet. Rebar tied the top 2-foot extension to the middle 2-foot extension. It was unknown prior to failure if the middle 2-foot extension was tied to the original wall with rebar. Interior drainage was provided by one permanent pump and temporary pumps as needed during flood events and by gravity through 4-inch drainage holes in the wall bottom during nonflood periods. The drainage holes were plugged with inflatable rubber "balloons" during flood events. The total floodwall length was about 880 feet. Closures in the wall consisted of boards placed in a slot in the floodwall and made watertight with asphalt roofing material, jute packing, and plastic sheeting.

**Lesson.** About 150 feet of the wall collapsed at the seam between the original wall and the first 2-foot extension. Of the 150-foot section that failed, a 90-foot section had foundation failure. Both failures occurred because (1) the original wall footing was not designed for extensions doubling the original wall height and (2) the assumption that rebar tied the first extension to the original wall was false. Upon wall failure and due in part to the close proximity of the wall to the building, the building roof subsequently failed. After the flood, the building was being abandoned and the industry was relocating to a flood-free site.



Looking at the floodwall. Note the closures at left and far right, the original floodwall, and the two additions. The failed portion is between the building and the trees in the background.



Looking at the original floodwall. Note the foundation failure resulting in wall misalignment. Also, note the absence of rebars on the original floodwall.



Looking at the collapsed floodwall additions. Note these two additions are still tied together with rebar.

## CENTRAL IOWA

Central Iowa in the summer of 1993 was similar to most parts of the Upper Midwest in that wet antecedent moisture conditions existed as a result of abnormally wet conditions beginning in the fall of 1992 and continuing through the following season. In the Ames, Iowa, area, the climax in terms of flood stages to these wet conditions occurred on July 9, 1993, when Squaw Creek reached a record flood elevation. The flood discharge was in excess of 21,000 cubic feet per second (c.f.s.), as compared to the published FIS 100-year discharge of 8800 c.f.s.

## **AMES, IOWA**

Structures 57 and 58 had been built since approximately 1970. At the time of construction, they were both flood proofed to protect against a 100-year flood event. The 1993 event was so much larger than a 100-year event that the flood proofing systems were simply exceeded. However, some lessons can still be learned from these two structures.

**STRUCTURE 57.** This large structure had interior floors lower than the 100-year flood elevation. The major path of floodwater entry was at the top of an east-side ramp down to the lower level. The top of this ramp failed due to underseepage and overtopping. Another point of floodwater entry was the pedestrian doors, which were made of glass in metal frames.

**Lesson.** Ultimate failure occurred because of the record flood elevation, which exceeded the design elevation. However, prior to that elevation being reached, problems were occurring due to the lack of floodshields at the pedestrian door and at the top of the ramp. Underseepage cutoff walls were needed at the ramp to prevent the occurrence of the underseepage. With flood proofing to accommodate the record 1993 flood, increased hydrostatic force would require the sealing of all underground conduits entering the building and the placement of manual shutoff valves on all sanitary sewer lines. Interior sump pumps were operated by an emergency generator, which operated on city water for cooling. A backup closed cooling system is needed to ensure operation during floods. Operation of the pumping system is critical to relieving seepage due to hydrostatic force.

**STRUCTURE 58.** This large structure was located in close proximity to Structure 57. The building was flood proofed by elevation in excess of 1.5 feet above the 100-year flood elevation. Floodwater entry to the building was primarily through doors and windows.

**Lesson.** The existing flood proofing system was adequate for the design flood but was inadequate for the 1993 flood. Floodshields need to be installed at all openings. All conduit entrances to the building need to be sealed and manual shutoff valves installed in sanitary sewer lines as a precaution against water entry due to increased hydrostatic pressure for a flood proofing system design to accommodate the 1993 flood elevation.

## **SOUTHEASTERN TEXAS**

The flooding in the fall of 1994 in the Houston, Texas area, resulted from extremely heavy rainfall in the San Jacinto River basin. Flooding in the eastern Houston metropolitan area was characterized by large depths combined with areas of extreme high velocity.